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Outdoor RF spectral study available from cell-phone towers in sub-urban areas for ambient RF energy harvesting

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Abstract. In this paper, outdoor RF spectral survey results in a sub-urban area are demonstrated. This work was carried out to explore and define the ambient RF signal sources available in the populated environment so as to select the frequency bands most suitable for designing RF energy harvesting circuits. Referring to the Egyptian frequency allocation chart, the ambient RF power sources within the spectrum of 0.5 to 2.2 GHz have been detected and measured to cover the mobile downlink frequency bands (2G, 3G and 4G) and the digital TV broadcasting bands which represent the most favourable frequencies for ambient RF energy harvesting circuits which is convenient for outdoor applications that need a power supply source in the range of microwatts. According to the available parameters of the cellular network standards, the measurement results were compared with the analytical empirical path loss propagation models focusing on sub-urban areas which provide an estimation of the median path loss as a function of distance and the urban terrain classification. The models that are discussed in this paper are HATA Model, Ericsson Model and ITU-R Model. It is found that HATA model can be used to give the best predictions with minimum error for losses and received power levels. Based on the measured data, a designer can decide the maximum distance away from a cell-phone tower that meets certain detection sensitivity. This study is useful for ambient RF energy harvesting designers.

1. Introduction

Cellular telephone, broadcast television and radio stations are considered to be excellent candidates of ambient RF energy sources available in most of the populated areas. The continuous availability (24/7) of such sources takes the intentions of many researchers in the last decade to make maximum utilization of these propagated signals as micro-power sources that could serve (IOT –I2OT, wireless sensor networks ‘WSN’, radio frequency identification ‘RFID’, etc.) applications.

Electromagnetic waves behaviour during its propagation is an important issue to understand in order to design an RF wireless power harvesting (WPH) system. The behaviour of electromagnetic waves varies according to the distance, frequency, and conducting environment [1]. Depending on the requirements of the application, the challenging issue in using the RF ambient energy sources is the design of a robust RF harvester, which can sustain high power conversion efficiency in spite of the fluctuations in the power levels received at the harvester antenna.

For better understanding of the factors and phenomena that affect the power levels of electromagnetic signals during its propagation in urban areas, many empirical models had been introduced concerning with different types of losses that the signal face while propagating from the transmitter antenna until it reaches the receiving antenna end [2].



Previous works reported concerning with RF spectral survey as in [3] a city-wide RF spectral survey was conducted in London covering the UHF (0.3–3 GHz) part of the frequency spectrum and stating that the most promising power density levels SBA (W/cm²) was measured in the cellular telephone (GSM900, GSM1800, and 3G) downlink frequency bands. Another outdoor RF spectral survey carried out in an urban area in Southern China reported in [4] covering the frequency band from (0.7 to 3) GHz and results showed that the most promising power levels had been measured at the CDMA800 downlink band (870 to 880MHz) with average power of about -38.99dB and the GSM900 downlink band (935 to 960MHz) with average power of about -50dBm. However in [5], the highest peak power level reported in an outdoor ambient RF power density measurements was -7 dBm (200 μ W) at (Place de la-République) in Paris. The electromagnetic power measurements performed at this location is generated by cellular operator in the GSM-1800, LTE-2600, and UMTS-2100 bands Ambient wireless power at the UHF digital TV-band (500–700) MHz in Tokyo, Japan, was reported in [6] with measured power from multiple channels of DTV broadcast source transmitting at 48kW at a distance of 6.3km away was (11.7–29 μ W).

The main purpose of this paper is to investigate the RF energy sources and identifying the frequency bands of operation of RF energy harvesters. Hence, comparing the obtained results with different propagation models of built up areas that suit our case study in order to get a realistic vision about the power levels available in real sub-urban environment which is very helpful in the design of RF energy harvesters and how to build a scenario for this harvesters to operate correctly.

2. Theoretical background

2.1. Wireless Communication Network Planning

One of the basic principles of wireless communication network planning such as cellular phone network is the network coverage and performance prediction prior installation and deployment. This is always done by careful study and analysis of all available data about the nature of the terrain where the network will be installed.

Taking into account the essential parameters affecting the network performance which are the effective isotropic radiated power(EIRP) transmitted from the base station, the signal strength at the receiver side (mobile station) and the losses the signal go through during its propagation starting from the transmitter antenna and ending at the receiver antenna side known as path loss. Figure 2 shows different types of losses which the signal may encounter during its propagation.

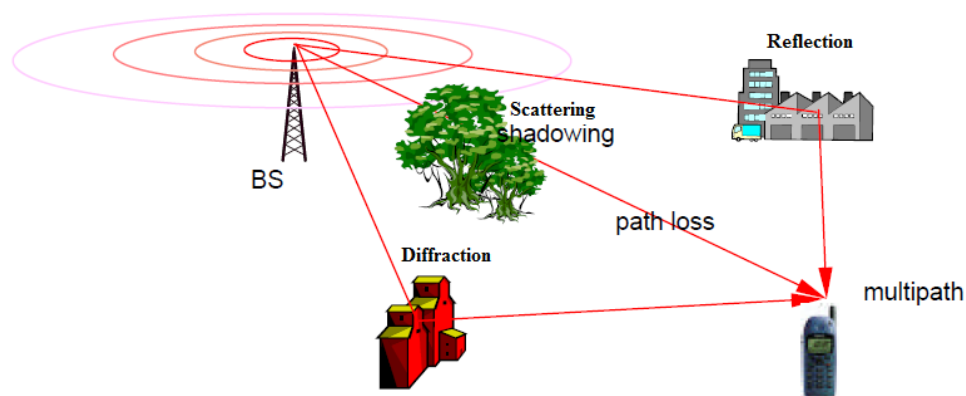


Figure 1. Different types of losses EM signal encounter during its propagation from the transmitter antenna to the receiver antenna side .

2.2. Propagation Models

2.2.1. HATA model

This model is an empirical formula that incorporates the graphical information from the Okumura model to predict the median path loss. This model is applicable for the range of frequency from (150-1500) MHz [2].

There are three different formulas for the HATA model:

For urban areas,

$$L_{50-urban}(dB) = 69.55 + 26.16 \log(f_c) - 13.82 \log(h_t) - a(h_r) + [44.9 + 6.55 \log(h_t)] \log(d) \quad (1)$$

Where

f_c is frequency of propagation in(MHz) , $150 < f_c < 1500$

h_t is height of the base antenna in(m), $30 < h_t < 200$

d is the propagation distance in(Km), $1 < d < 20$

$a(h_r)$ is the mobile antenna height correction factor:

$$a(h_r) = (1.1 \log(f_c) - 0.7)h_r - (1.56 \log(f_c) - 0.8) \quad (2)$$

h_r is the height of the receiver station in(m), $1 \leq h_r \leq 10$

For sub-urban areas,

$$L_{50-suburban}(dB) = L_{50-urban}(dB) - 4.78(\log(f_c))^2 + 18.33 \log(f_c) - 40.94 \quad (3)$$

For open areas,

$$L_{50-open\ areas}(dB) = L_{50-urban}(dB) - 2 \left(\log\left(\frac{f_c}{28}\right) \right)^2 - 5.4 \quad (4)$$

2.2.2. Ericsson Model

This model is the path loss calculation of the Ericsson 9999. It is the Ericsson's implementation of HATA model and it is widely used in cellular network coverage planning in which the path loss is given as: -

$$P_L(dB) = a_0 + a_1 \log(d) + a_2 \log h_b + a_3 \log(h_b) \log(d) - 3.2(\log 11.75(h_m))^2 + g(f) \quad (5)$$

Where;

a_0, a_1, a_2 and a_3 are constant parameters related to the type of the propagation medium [6].

Default values are $a_0 = 36.2$, $a_1 = 30.2$, $a_2 = 12$, and $a_3 = 0.4$.

h_b is the effective transmitter antenna height in meter ranging from 30m to 200m,

h_m is the effective receiver antenna height in meter ranging from 1m to 10m.

d is the distance between Base Station (Bs) and the receiver mobile station (Ms) in Km.

And $g(f) = 44.9 - \log(f_c) - 4.78(\log(f_c))^2$

2.2.3. ITU-R Model

The ITU-R model is to be used for the outdoor to indoor and street level path loss prediction in urban and suburban environment for Non-Line of Sight (NLOS) case describing worst condition deviation of 10dB for outdoor users [7], The path loss is given as: -

$$P_L(dB) = 40 \log(d) + 30 \log(f_c) + 49 \quad (6)$$

Where:

d is the propagation distance in Km

The ITU-R model is applicable for the range of propagation frequency f_c up to 2GHz.

3. Measurements

3.1. Egyptian Frequency Band Allocation

Based on the Radio frequency chart of Egypt [8] published by the Egyptian National Telecommunications Regulatory Authority (NTRA) which identifies the allocation of frequency bands of different radio services and according to our RF spectral survey the ambient RF sources from digital TV broadcasting (DTV) and cellular telephone service providers available are as follows

1. DTV Broadcasting Channels in Cairo rural areas are: -
 - UHF-32 which is 8 MHz channel (558-566) MHz
 - UHF-36 which is 8 MHz channel (590-598) MHz
2. Mobile Networks Frequency Allocation (4-operators)
 - GSM 900 :(890 - 915) MHz uplink, (925 - 960) MHz downlink.
 - GSM 1800: (1710 – 1785) MHz uplink, (1805 – 1880) MHz downlink.
 - UMTS/3G :(1920 - 1980) MHz uplink, (2110 – 2170) MHz downlink.

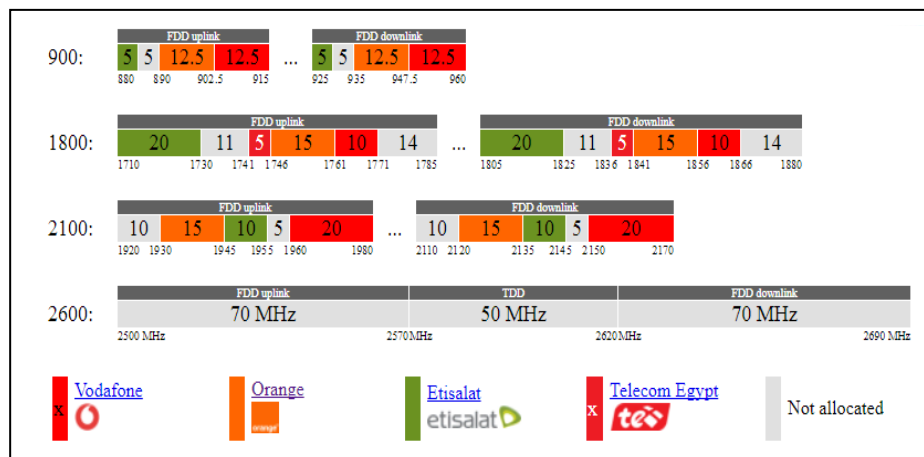


Figure 2. Detailed mobile network frequency spectrum allocation on the Cellular network (4 operators) in Egypt [9].

3.2. RF Spectral Survey Measurement Setup

The spectral survey measurements was carried out at an outdoor sub-urban area in Cairo using Anritsu Master™ MS2720T spectrum analyser [10] Connected to a broadband Double-Ridged guide antenna (Horn EO-3106B) operating from 200 to 3000 MHz with variable antenna gain as stated in [11]. Figure 3 shows the measurement setup.

The DTV Broadcasting channels (UHF32 and UHF36) was detected at a distance (d) of about 3.2Km away from the terrestrial transmission tower, the cellular network signals were detected at a distance of about 1Km away from the telecom tower base transmitting station (BTS).

The measured power levels from the available RF power sources (DTV Broadcasting and Cellular BTS) listed in table. 1 accompanied by the distance separating the transmitters from the measurement location and the signal shape of each band from the Anritsu Spectrum Master™ are illustrated in figure 4 and figure 5.

3.2.1. Path Loss and Received Power Calculation

For a wireless communication system, a typical link budget equation consists of all gains and losses in a transmission system in order to calculate the signal strength at the receiver end at a distance (d) away from the transmitter end and this equation expressed as [12]:

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{TX} - L_{FS} - L_{FM} - L_{RX} \quad (7)$$

Where:

P_{RX} = Received power (dBm), P_{TX} = Output power of the transmitter (dBm),

G_{TX} = Antenna gain of the transmitter (dBi), G_{RX} = Antenna gain of the receiver (dBi),

L_{TX} = Feeder and connector losses (Transmitter) (dB), L_{FS} = Free space loss or path loss (dB)

L_{FM} = Signal propagation losses (these include fading margin, polarization mismatch, losses associated with signal propagation medium, other losses...) (dB), L_{RX} = Feeder losses (Receiver) (dB)

Table 1. Measured RF power levels from DTV broadcasting channels (UHF32, UHF36), cellular network frequencies (GSM900, GSM1800 and 3G).

NO.	RF frequency band	Received Power P_{Rx} at C.F. (dBm)	Distance(d)away from Tx. in (Km)
1	UHF32 (558 – 566)MHz	-60	3.2
2	UHF36 (590 – 598)MHz	-60	
3	GSM-900 FDD downlink (925 – 960)MHz	-50	1
4	GSM-1800 FDD downlink (1805–1880)MHz	-45	
5	UMTS/3G FDD downlink (2110 – 2170) MHz	-60	



Figure 3. The spectral survey measurement setup.

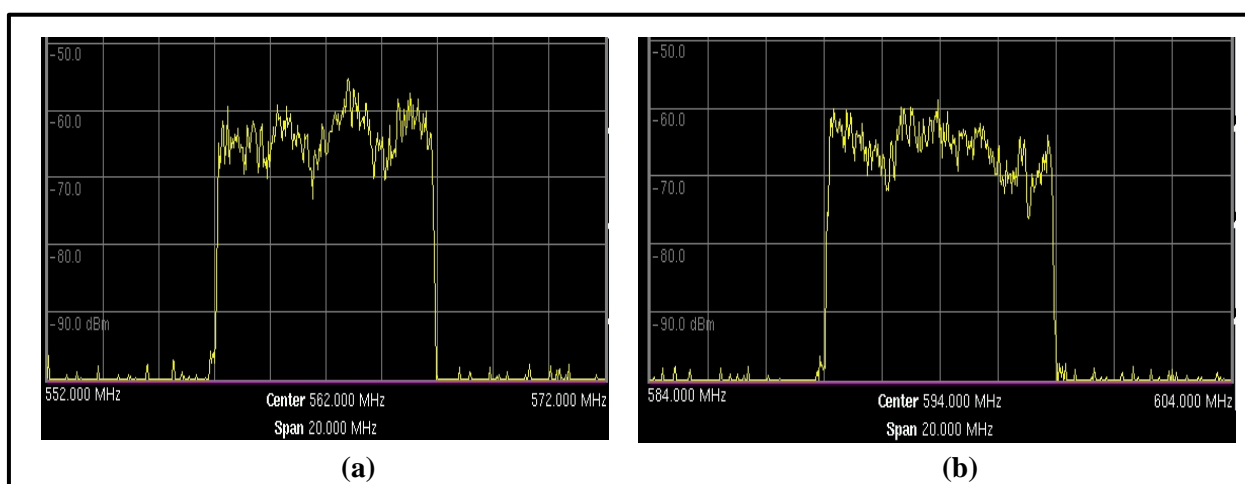


Figure 4. The spectral survey measurements at the selected frequency bands of the DTV broadcasting channels in Cairo (a) UHF32-DTV channel,(b) UHF36-DTV channel

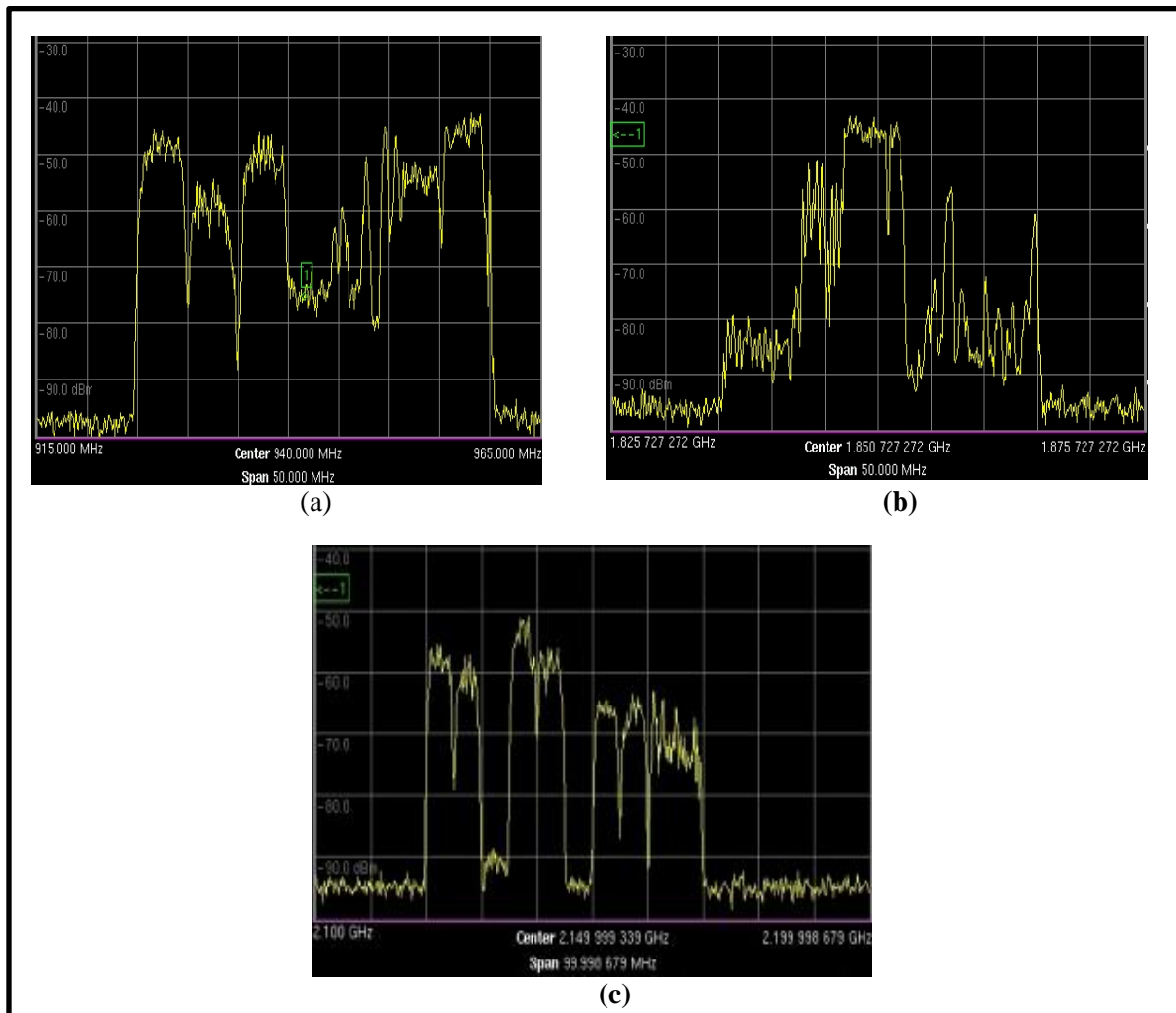


Figure 5. The spectral survey measurements at the selected frequency bands of the cellular network downlinks (a) GSM-900 FDD ,(b) GSM-1800 FDD (c) UMTS/3G FDD.

Hence, we can calculate the path loss based on the previously discussed models in section II and the received power based on the link budget equation to verify the measurements taken based on the transmitter and receiver parameters.

- The telecom tower Tx. (BTS) parameters:
 $P_{TX} = 43\text{dBm}$, $G_{TX} = 18\text{dBi}$, $L_{TX} = 4\text{ dB}$, and $h_t = 30\text{ m}$ (BTS effective antenna height).
- The receiver end parameters:
 $d = 1\text{ Km}$ (distance between BTS and Rx), $h_r = 1.5\text{ m}$ (The effective Rx antenna height),
 $G_{RX} = \text{range from } 4.2\text{ to } 10.6$ (Horn EO-3106B datasheet),
 $L_{RX} = 1\text{dBm}$ (cable losses between antenna and the spectrum master).

Assuming that $L_{FM} = 8\text{dBm}$ at the receiver end at a distance of 1Km in a sub-urban area including fading margin and polarization mismatch.

The calculated values of the median path loss predictions and the received power strength for this case study at the cellular network bands of (GSM-900, GSM-1800 and UMTS/3G) downlinks listed in table 2.

Table 2. Median path loss based on the discussed path loss models for built up areas and the associated received power calculated compared with the survey measurements.

No.	Path loss & P_{Rx}	GSM-900 ($f_c = 940\text{MHz}$)	GSM-1800 ($f_c = 1850\text{MHz}$)	UMTS/3G ($f_c = 2145\text{MHz}$)
1	HATA model $L_{50\text{-suburban}}$ (dB)	99.5	104	104.5
	Calculated P_{Rx} (dBm)	-43.5	-46	-47
2	Ericsson 9999 Model P_L (dB)	138.8	143.15	143.98
	Calculated P_{Rx} (dBm)	-73.8	-76.15	-77.48
3	ITU-R Model P_L (dB)	138.2	147	149
	Calculated P_{Rx} (dBm)	-81.2	-78	-81
	RF survey P_{Rx} (dBm)	-50	-45	-55

4. Results and Discussion

When comparing the analytic substitution in the path loss empirical models (HATA, Ericsson 9999, ITU-R) with the measured values from the spectral survey at the cellular networks frequency bands, the nearest results for our case measurements was found to be the HATA model for suburban areas.

The calculated received power results based on Ericsson9999 and ITU-R path loss models was found to be far from the measured values from the survey as those two models suits for built up areas and try to give the worst case of the detected signal strength at rural areas. However, the power (P_{Rx}) calculated based on these two models could give a realistic vision for cellular network planners concerning with the quality of service that the network provides in areas with high building densities and more irregularities in shapes and heights.

Accordingly, we may know validate the HATA model and the link budget equations to predict a scenario for the effective range of distances (d) for RF energy harvesters optimized to operate effectively under the following conditions:

- (1) RF signal input power ranging from (-35 to -15) dBm.
- (2) The matched frequency bands of operation are GSM-900, GSM-1800, and 3G downlinks.

As an example for the proposed RF energy harvesting operation scenario, the calculated distances associated with the RF signal input power at the three-downlink frequency bands of the cellular network are listed in table 3 with the results plotted in figure 6.

Table 3: Calculated distances at which an RF harvester of a typical sensitivity to the available input power can operate at the downlink frequency bands of the cellular network with $f_c = (950, 1850, 2145)$ MHz

NO.	RF signal I/P power $P_{Rx,in}$ (dBm)	Distance(d)(Km) at $f_c = 950\text{MHz}$	Distance(d)(Km) at $f_c = 1850\text{MHz}$	Distance(d)(Km) at $f_c = 2145\text{MHz}$
1	-15	0.170	0.151	0.134
2	-20	0.240	0.209	0.186
3	-25	0.330	0.290	0.259
4	-30	0.460	0.402	0.359
5	-35	0.640	0.557	0.498

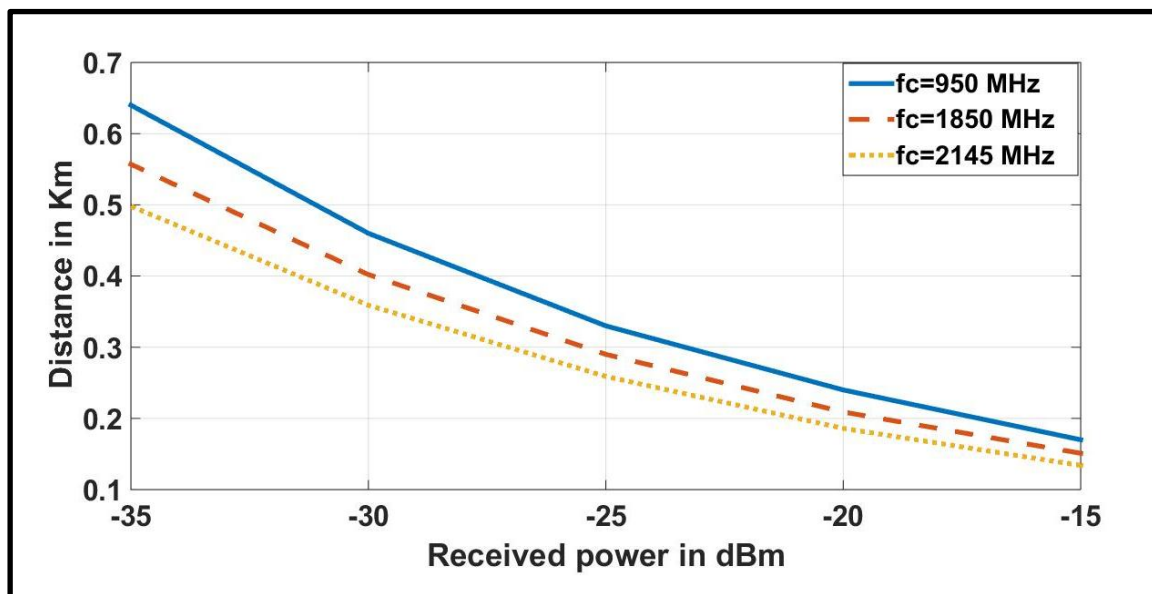


Figure 6. Predicted operation ranges of RF harvesters operating at the downlink frequency bands of the cellular network.

5. Conclusion

The main objective of this paper is to predict the available outdoor ambient RF signals to help the harvester designers estimating the required distance from the signal source focused on certain sensitivity of a selected detector. The ambient RF power levels within the spectrum of 0.5 to 2.2 GHz measured to cover the mobile downlink frequency bands (2G, 3G and 4G) and the digital TV broadcast band. According to the available parameters of the cellular network standards, the results compared with the analytical empirical path loss propagation models focusing on sub-urban areas, which provide a measure of the median path loss as a function of distance and urban terrain classification. The models discussed in this paper are HATA Model, Ericsson Model, and ITU-R Model. It was found that HATA model could be used to give the best predictions with minimum error for the losses and the received power levels.

In addition, measurements and results obtained from this case study help a designer to select an energy harvester with certain detection sensitivity and predict the required distance from the cell-phone tower which is corresponding to the available service standard (950,1850, 2145) MHz frequencies. For example, an RF harvesting circuit optimized at an input power of -20 dBm operating at 950 MHz can operate efficiently at a distance of 240 meters away from a cellular network tower (BTS) at a sub-urban area.

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